74028

Armed Services Technical Information Agency

UNCLASSIFIED

AD074028

CHABA

REPORT NO. 3

of the

ARMED FORCES - NATIONAL RESEARCH COUNCIL
COMMITTEE ON HEARING AND BIO-ACOUSTICS

The Effects of Blast Phenomena on Man: A Critical Review

by Donald H. Eldredge
with a
SELECTED BIBLIOGRAPHY
prepared with the assistance of
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Approved by the CHABA Council, June 1955

Published By

ARMED FORCES - NATIONAL RESEARCH COUNCIL
COMMITTEE ON HEARING AND BIO-ACOUSTICS

OFFICE OF THE EXECUTIVE SECRETARY
818 South Kingshighway
St. Louis 10, Missouri

PROJECT NR 140-069
CONTRACT Nonr-1151 (01)

Statement of Purposes and Methods of Operation

The Armed Forces - National Research Council Committee on Hearing and Bio-Acoustics (CHABA) was organized early in 1953 to provide consultation and advice to the Armed Forces in the general areas of (1) the effects and control of noise, (2) auditory discrimination, (3) speech communication, (4) the fundamental mechanism of hearing, and (5) auditory standards. The term "bio-acoustics" includes the direct non-auditory effects of high-intensity sound and vibration on man's body, the relevant physical and engineering problems of noise generation, measurement, and control, and the psychological and social reactions of man and of animals to noise. The activities of CHABA are supported equally by the Army, Navy, and the Air Force.

CHABA is not a contracting agency. It does not dispense funds, although it may recommend that research along certain lines be carried out. It is not itself a research organization. Its output is not data but advice.

The Executive Council of CHABA consists of nine members: one representative apiece from the Army, the Navy, and the Air Force, three members appointed by the National Research Council, and three members-at-large chosen by the appointed members of the Council. The full Committee on Hearing and Bio-Acoustics consists of about 30 regular members approximately equally balanced between military representatives and civilians appointed by the National Research Council. The latter appointments include "engineers and scientists . . . in the fields of acoustics, vibration, psychology, physiology, or medicine." There are also several affiliated members who represent other government agencies with interests in the general area.

The major work of CHABA is carried out by "working groups" of consultants. They deal with specific problems brought to the Executive Council by one of the service representatives on the Executive Council, or by the National Research Council. At least one or two of the members of each working group are already members of CHABA, but often outside consultants are also invited to serve. When a working group has prepared its report, the Executive Council has the responsibility for accepting and transmitting the report, either with or without additional comment or endorsement.

CHABA reports to the Armed Forces through the service representatives on the Executive Council. CHABA reports to the National Research Council Divisions of Physical Sciences, Medical Sciences, Anthropology and Psychology, Engineering and Industrial Research, and Biology and Agriculture. So equally divided are the interests that the committee is responsible directly to the office of the Chairman of the National Research Council, although the administrative details of liaison, distribution of reports, etc., are carried out through the Executive Secretary of the Division of Anthropology and Psychology.

Members of the Armed Forces desiring CHABA consulting services should submit their requests through the appropriate service representatives on the Executive Council. These are:

Army:

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Others desiring CHABA consulting services should submit their request through the Executive Secretary of the Division of Anthropology and Psychology of the National Research Council. He is:

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The committee as a whole meets at least annually. The program of each meeting of the full committee is carefully designed to take advantage of the interdisciplinary character of the membership. A thorough presentation of some major problem and its subsequent discussion by the members provides valuable insight for the specialists into the background and varied complexities of the problem. Opportunity is provided for the informal discussion of any problems that members wish to raise, with resultant clarification of the actual problems and possible recommendations for attacking them.

FOREWORD

The following critical review and selected bibliography on the subject of the Effects of Blast Phenomena on Man was prepared in the Secretarial Office of the Committee on Hearing and Bio-Acoustics by Dr. Donald H. Eldredge, Technical Aide and Shirley K. Hirsh, Administrative Assistant, in response to a request submitted by the Army representative on the CHABA Council.

The report has been reviewed and approved for publication by the CHABA Council. However, the opinions expressed in the review and the responsibility for the inclusion or the exclusion of particular papers lies with Dr. Eldredge as the author. The review and bibliography are not intended to be exhaustive. They include the material and the information judged by Dr. Eldredge to be most useful and significant for future workers on problems of blast. The members of the CHABA Council believe that Dr. Eldredge has used good care and judgment in his selection and presentation of material, but obviously are not in a position to judge the merits of papers that are not included. The scientific opinions and generalizations are those of Dr. Eldredge, and the CHABA Council publishes them in the belief that they are useful and give an adequate introduction to the problems that are considered.

HALLOWELL DAVIS
Executive Secretary

THE EFFECTS OF BLAST PHENOMENA ON MAN

A REVIEW FOR THE COUNCIL OF THE COMMITTEE ON HEARING AND BIO-ACOUSTICS

I. Task

In response to a letter from Colonel C. S. Gersoni, Office of the Surgeon General, Army, to Dr. Aram Glorig, Army Representative on the CHABA Council, and at the direction of the CHABA Council, the staff of the Executive Secretary has reviewed the open literature dealing with the effects of blast on man. Colonel Gersoni outlined three general areas in which blast might have a deleterious effect on military personnel. These were:

"1. The effect of blast on decrement of performance of crews (field artillery crews, rocket launching crews, guided missile crews, etc.).

2. The effect of blast on behavior of crews.

3. The effect of repeated blast for prolonged periods of time on the body with particular reference to pathological conditions produced."

In a letter to the Executive Secretary, dated 4 April 1955, Major James P. Albrite, present Army Representative on the CHABA Council, enlarged on certain aspects of the above problems with the following more specific questions:

"1. What is the present status of research on the ear defender? What ear defenders are recommended? What are the techniques recommended to test the attenuation properties of the ear defender? We would like to have information on ear defenders that are available in the commercial field . . .

2. What are the methods for accurate measurement of blast? How would you define blast? What are the components of blast?

3. What is the pathology of the ear or other parts of the body due to blast? . . .

4. What would you suggest as an outline for a program aimed to protect soldiers and civilians in the Army who are exposed to blast and high-intensity noise, keeping in mind present-day knowledge and recommendations for future research in this field?"

The open literature dealing directly with blast injury to man and experimental animals is not extensive and is principally concerned with injury to the ear, body injuries sufficiently severe to produce combat casualties, cerebral blast concussion, and battle fatigue or hysteric-anxiety state. In few cases is there significant effort to relate injury to the physical stimulus quantitatively. The literature that may be useful in planning procedures for the diagnosis and measurement of the possible effects included in Colonel Gersoni's questions is extremely varied and extensive. We believe we have included most of the important open literature on blast. We have intentionally eliminated several references because they seem out of date or are inaccessible. Also included is a selected bibliography recently prepared by D. G. Doehring and W. D. Ward of the Central Institute for the Deaf. This literature deals largely with specific methods and techniques that have been used to measure possible impairment of function.

In the following summary, we have attempted to extract and to organize the important studies

and hypotheses encountered. To a considerable degree, this process has been supplemented by experience gained with high-intensity sound. An effort has been made to make the physics section intelligible to those trained in biological sciences, and vice versa. Approached in this way, precision and conciseness are lost to some degree but the presentation should be more useful. Also in the interests of intelligibility and perspective, detailed reporting of experimental results has been kept to a minimum.

We have not attempted here to answer directly any of the questions that led to this review. It soon became apparent that direct answers could not be obtained in most instances. The specific questions related to ear protectors we believed were peripheral to the central themes of this review and will be dealt with separately. Instead we have tried to write this review in a way that will provide sound bases for future research planning. This is really only a first step. A second step might attempt to outline in general terms the kinds of new knowledge that should be acquired. After this step, each of many specific questions will require further detailed theoretical and experimental consideration. Without a comprehensive basic approach, important questions will remain unanswered and individual studies will be more difficult to relate in meaningful patterns.

II. The Physical Stimuli

In approaching this problem, we have included under the category "blast" all of the physical events that characterize very rapid combustion, explosions, and detonations. The significant difference among these categories is the rate at which the chemical transformation takes place. This rate in turn determines the nature of the particular physical changes in the environment that are produced by the reaction. The common factor is the rapid conversion of solid or fluid in a small volume to gas under pressure in the same volume.

Jet engines, particularly with after burners, rocket engines, and the combustion of fuel in the cylinder of a "knockless" internal combustion engine constitute examples of very rapid combustion. Explosions occur with the ignition of slow gun powder, primer materials, and gases or dusts in air. The term "detonation" is usually reserved for the reaction produced by high explosives such as nitroglycerine, trinitrotoluene, and tetryl. In varying degrees each of the above reactions in air produces four physical phenomena. These are 1) blast, 2) shock waves, 3) sound of "finite" dimensions,* and 4) sound of usual or infinitesimal dimensions. Often it is difficult for the nonphysicist to distinguish among these phenomena that are so closely tied to what to the ear and eye appears to be a single event. It is perhaps helpful to understand first, that there is a sequence of events, even though the time scale is short, and second, that blast, shock waves, finite sound and usual sound actually behave differently and require different mathematical treatments for their description.

Blast properly refers to the escape of the gaseous products of combustion from the high-pressure small-volume state to a volume compatible with ambient pressure. A measure of blast is the initial velocity and turbulence of the expanding gas. These initial blast velocities are about the same as the rate of chemical reaction, and in a detonation may reach 20,000 to 25,000 feet per second or nearly 20,000 miles per hour. In such

* For example, the peak positive pressure of a pure tone at 120 db above the standard reference of .0002 dynes per cm^2 is about .00028 atmospheres. This is about the loudest sound level encountered in ordinary experience and is uncomfortable for the ear. We shall consider sound to assume "finite" dimensions when the peak pressures are greater than .002 atmospheres.

cases the turbulence is extreme. Blast as such is not an oscillatory phenomenon, but is the one-way flow from center outwards. The entire phenomenon is confined to a relatively small volume around the center of the reaction. For example, Robinson[1] reports that the maximum travel of the blast of a 500-pound bomb is about 25 feet. The directional pattern of a blast depends on the avenues of escape for the gases that are either already available or produced by the blast.

In the present context, blast is the phenomenon which is used to do work. Usually the work is mechanical such as propelling missiles, aircraft, shells, or bullets. Even the exploding shell accomplishes most of its destruction mechanically through the action of the secondary fragments of casing and target that are propelled at high velocity for considerable distances by the force of the explosion.

Extremely high temperatures are also associated with the high-pressure small-volume state of the blast gases. Within the context of this review this heat is not important.

A shock wave is physically characterized by a wave front showing discontinuity between particle density and particle acceleration. In ordinary acoustics the highest particle accelerations occur synchronously with the extremes of particle density, i. e., condensation and rarefaction. Furthermore, particle acceleration is proportional to the instantaneous particle density. In shock waves, however, the change with time of particle acceleration is quite different from the change with time of particle density, and particle acceleration is not proportional to particle density. Associated with these discontinuities are very high particle velocities within the wave front. The shock wave is a disturbance in the medium (solid, liquid, or gaseous) produced by the initial blast energy. This disturbance travels in the medium by transfer of energy from particle to particle in an oscillatory manner as distinguished from the direct travel of particles in the blast itself. Outside the immediate blast area, propagation of the shock wave is spherical as in ordinary acoustics. Shock waves are reflected by obstacles and in the process they show pressure doubling. The nature of the medium and the nature of the blast together determine the peak pressure at the source and the initial duration of the positive shock impulse.

As in acoustics, the density, pressure, temperature, specific heat, and coefficients of viscosity and heat exchange of the medium determine the characteristics of the medium for shock waves. Also, any medium will be asymmetrical in regard to shock waves to the extent that pressures below the resting state are limited by zero, whereas pressures above the resting state are essentially unlimited.

Although the shock wave undergoes spherical divergence like ordinary sound waves, its energy decreases with distance faster than the inverse square law predicts. This is largely because the physical properties of the medium, particularly the viscous and elastic properties, are such that the discontinuities between particle density and particle acceleration can not occur adiabatically; that is, without loss of energy in the form of heat to the medium. This loss tends to "smooth out" a shock wave, largely by reduction of the peak pressure and the abruptness of the discontinuities. On the other hand, a sound or shock wave travels faster as the density of the medium is increased. In the case of shock waves the density of the medium in the condensation phase is greater than the density of the medium at rest or in the rarefaction phase to such a degree that the velocity of propagation is significantly greater in the condensation phase. The condensation peak front thus precedes in time (and phase angle) the peak condensation that would be anticipated from the sinusoidal behavior of classical acoustics. This sharpens the wave front and maintains the discontinuities between particle density and acceleration. Obviously a shock wave ultimately decays into a classical acoustic wave in spite of this

tendency because of the energy losses introduced by the inverse square law and the viscosity of the medium.

The above physical features of the initial blast and the subsequent transmission of shock waves in a medium introduce two other characteristics of shock waves. First, because of asymmetry of the medium, the short initial condensation or positive pressure phase of a shock wave, which lasts about five to ten milliseconds, is followed by a much longer rarefaction or low pressure phase of the order of 25 to 50 milliseconds. As the energy of explosion is increased this approximate ratio between the durations of the phases is preserved even though condensation phases lasting as long as one second are encountered. Second, depending on the peak pressure, shock waves travel somewhat faster than sound. Under usual circumstances, in air near its source a shock wave will travel two to three times as fast as sound. The velocity of the shock wave front may be even higher initially, but ultimately it decreases to the velocity of sound as the pressure decays to usual acoustic pressures.

In conceptually relating the blast wave to the shock wave as they occur in an explosion in air, it is perhaps useful to consider shock waves that are generated in the absence of an explosion. Any object that travels through air faster than sound generates shock waves at its leading and trailing edges. The crack of a whip is a shock wave so generated. Similarly, the crack heard from a supersonic bullet as it passes is a shock wave. When a solid object travels through air at velocities less than sound, the pressure at its leading edge creates a pressure wave disturbance which is transmitted ahead of the moving object with the velocity of sound. The undisturbed medium ahead first is disturbed by this pressure wave. As the object approaches, the amplitude of the pressure wave gradually increases to the pressure at the leading edge of the object. This pressure wave in effect "pierces" the medium ahead, pushing (accelerating and compressing) the air molecules aside to allow the object to pass through the medium.

When an object moves through air with velocities greater than sound, the pressure wave is confined to the leading edge of the object and is not propagated ahead. Thus the pressure wave and the object strike undisturbed air almost simultaneously, imparting high accelerations to particles before they have had time to move to positions they will have at the maximum particle density state. This disturbance at the leading edge must travel with the velocity of the object, but on either side of the object its velocity rapidly decreases to sonic velocity and lags far behind the object itself. The shape of the pressure disturbance is then quite similar to the bow wave created by a boat in water.

In the case of an explosion it is the expanding gases traveling outward from the small-volume high-pressure state with velocities greater than sound that meet undisturbed air and create a shock wave. Under these circumstances the blast wave front and the shock wave front are indistinguishable. As the velocity of the blast wave front decreases to and below sonic velocity, the shock waves separate and continue on, with supersonic velocities at first. The shock waves rapidly slow down, however, to sonic velocities, as is the case with shock waves generated by solid objects traveling in air. Since the disturbance is spherical there is not an opportunity for the disturbance to assume the configuration of the bow wave of a boat.

Miller[2] measured the shock waves generated by large artillery. In this case the shock waves are generated spherically by a moving blast source. This case demonstrates features of shock wave formation common to both of the cases described above and is worth reading in the original.

Sound waves of finite amplitude occupy an intermediate position between shock waves and

classical sound waves of infinitesimal magnitude. A shock wave decays through this state before it becomes an ordinary sound wave. The distinctions between ordinary sound waves, "finite" sound waves and small discrete shock waves is primarily quantitative and rather arbitrary. For instance, one can classify aperiodic waves with inital peak pressures in excess of one atmosphere as discrete shock waves, periodic waves with peak pressures of less than one atmosphere but more than 0.008 atmospheres as sound waves of finite amplitude, and waves with peak pressures less than 0.008 atmospheres as ordinary sound waves. Sound waves of finite amplitude, like shock waves, show spherical divergence, somewhat more loss of energy with distance than the square law would predict, and steep wave fronts. The mathematics for sound waves of finite amplitude is not so well developed as for the other forms of energy under consideration here, because of this transitional character and because interest in the subject is relatively recent. Ordinarily such sound is not considered separately in explosion studies. However, for the purposes of this study separate consideration seems advantageous for two reasons. In the first place, sound waves of finite amplitude, as well as small discrete shock waves, are abundantly produced by the blasts of jet and rocket engines. In the second place, sound waves of finite amplitude require separate sets of instruments for their measurement.

Classical sound waves of usual or infinitesimal dimensions appear ultimately at some distance from the point of the explosive reaction. The behavior of the energy in this form follows the usual rules for acoustics and the measurement procedures are reasonably well standardized.

The details of the preceding outline of the physical phenomena associated with explosive reactions may be altered when the reaction is controlled in order to do "work." Measurements made near large guns, for an instance, may show several peak pressure waves separated in time by a few milliseconds. These peaks can be variously associated with such events as the firing of the charges within the gun breech, the escape and passage of the missile, and the blast of gases exhausting from the gun barrel.

III. Measurement of the Physical Stimuli

In many respects measurement of blast phenomena falls short of being ideal. Instruments exist or can be designed to measure most of the features that are likely to have practical importance in the biological area. **The most important handicap at present would appear to be a lack of knowledge as to which features of blast phenomena should be measured to correlate with particular injuries.** Over and above this, the discontinuity of particle density and particle acceleration in a transient phenomenon creates difficulties in interpreting the measurements of blast phenomena. There are semantic difficulties involving the operational significance or "real" meaning of many terms used in ordinary acoustics when they are applied to shock waves. Condensation and compression (or pressure) are no longer proportional. Time also becomes critical, particularly at both ends of the continuum of durations extending from the brief duration of a detonation to the long durations of some of the pressure fluctuations observed around rocket engines. There are no devices which respond fast enough to follow the time course of the peak pressure of a detonation without some degree of distortion. On the other hand, the pressure fluctuations of the order of one cycle per second observed around some rocket engines require that the measuring device and associated equipment be capable of recording static as well as dynamic pressure in order to describe the event appropriately.

Blast Waves

This review has not included a detailed search of the literature for instruments suitable for measuring blast pressures. In the literature cited various mechanical and piezo-electric gauges have been used with reasonable success In many instances the response of the gauge appears to have been too slow to measure peak pressure, but as often as not may well have given readings that correlated well with the effects on other objects. Where blast pressures develop more slowly than they do in a detonation some of the gauges may respond rapidly enough to give a reasonably good measure of the peak pressures.

Shock Waves

Instruments that have been used to measure shock waves fall in two classes. This is because two aspects of a shock wave, condensation or pressure,[a] may be measured. One measure of condensation is the change in the **index of refraction of light** in the air through which the shock wave passes. This same phenomenon is used to show shock waves photographically in the **Schlieren-methode** and subsequent modifications of this technique. In general, methods employing this principle can be quite accurate and have the advantages that go with eliminating inertia from the measuring system. Unfortunately pressure cannot be directly derived from a measure of condensation, and pressure appears to have the greater practical significance.

Condensation can also be measured, but not so precisely, by the propagation of a shock wave through an **interferometer field.** A third principle which has been used with some success to measure condensation is embodied in the **"corona microphone."** The corona current leakage between high voltage electrodes depends among other things on the density of the air between the electrodes. These changes in current flow are thus a measure of condensation.

More devices exist for the measurement of pressure. These are "ballistic" devices with transient responses appropriate to their physical design. To measure pressure, a part (with mass) held in place by elastic connections (with damping) must move. Because of inertia the time required for this motion is not always small compared to the duration of the applied pressure. For this reason few if any of these devices record the peak pressures of very brief shock waves. However, several can be dynamically calibrated to give reasonable approximations of peak pressures.

Mechanical gauges operated as ballistic instruments can give a measure of the effective mean shock and the dynamic air flow at the wave front. Such devices include the baroscope of Miller, the "swinging" door ballistic meter, and the simple set of paper diaphragms. The Hopkinson bar and variations on this principle have been used to measure the pressure delivered during the first or condensation phase of a shock wave. One end of a bar is exposed to the shock wave. Loosely coupled to the other end with vaseline is a short section of the same material and diameter. The energy of the shock wave kicks off the short section with momentum proportional to the mean force transmitted by the wave. A ballistic meter may be used to catch the short piece and measure this momentum. This technique is very interesting but the information it gives is not so generally useful as that given by some of the other devices which record the variation of pressure in time. Under special circumstances the technique may prove useful and economical for monitoring or for comparative measurements of effective shock wave pressures. Since these devices do not record the time course of the pressure changes, this use assumes that, as described later in this section, the particular arrangement used can be designed to respond in the same way as the tissues or structures with which the study of pressure is concerned.

Piezo-electric gauges can be calibrated to give a good approximation of maximum pressures. As measured, these pressures also include dynamic

pressures and the pressure doubling phenomenon. Piezo-electric devices are subject to some errors that may trap the unwary. It is usually necessary to connect the crystals with short electric cables to either the recording apparatus or to a vacuum tube amplifier. The elements in a vacuum tube will vibrate in response to shock waves or sound waves and give spurious electrical signals. Either the desired electrical signal from the gauge must be made large compared to the spurious signal by designing the gauge so that it is more sensitive than the elements of the vacuum tube, or else the vacuum tube must be placed in an environment which receives less energy than the gauge.

Because of the nature of the crystals suitable for use in gauges and because of other circuit considerations, the measurement of high pressures requires gauges of low sensitivity. Thus the environment of the vacuum tube becomes critical. In measuring gun pressures where the pressure may be applied by a piston to the gauge, and the associated vacuum tubes are outside of the high pressure environment, the problem is not so great. However, in measuring pressures in free space it may be quite difficult to provide protection for a vacuum tube.

Work with piezo-electric microphones in acoustics has revealed another potential source of error. Mechanical resonances between the crystal and its structural support can lead to resonance phenomena and associated changes in sensitivity, phase, etc., that cannot be predicted from the resonance characteristics of the crystal itself. This difficulty may be largely avoided by careful design and by careful dynamic calibration of the device.

The condenser microphone may also be adapted to measure shock wave pressures. Usually these microphones are more sensitive than piezo-electric gauges and cannot be used for such high pressures. The same problems with associated vacuum tubes are encountered as with piezo-electric gauges. The response of the microphone to transient phenomena can be very good. By sealing the chamber behind the diaphragm and by using the capacity changes in the microphone to modulate a carrier frequency, the condenser microphone can be used to measure pressure changes as slow as 0.1 cycles per second. Except for measurement of the highest pressures, and possibly even there, the condenser microphone principle appears to have the best overall potentialities.

Sound of Finite Amplitude

The instruments most useful for measuring sound of finite amplitude are the **condenser microphone and the piezo-electric microphone.** The statements made above with regard to the use of these instruments to measure shock wave pressures also apply here. In recent years, interest in such sound as that produced near the jet engine has encouraged the development of designs suitable for this pressure range. Although very useful, these particular instruments cannot be used properly without a clear understanding of their basic limitations and the possibilities that remain for erroneous or spurious responses.

Sound of Infinitesimal Dimensions

The instruments used for measuring sound of infinitesimal magnitude are quite well standardized. Pitfalls in calibration, use, and interpretation remain but are relatively well known. Beranek[4] has recently covered this area quite completely.

In summary, methods do not exist that are adequate to describe completely and in general terms all the physical phenomena associated with blast and shock waves. Each instrument responds to these phenomena according to its own characteristics. In most instances, however, it should be possible to choose or to design instruments that will give meaningful measurements for practical studies.

IV. The Response of Human Tissues to Transient Forces

It has been stated above that the various pressure gauges do not respond instantaneously to the peak pressures of shock waves. They respond at varying rates depending on the masses, elastic forces, and damping forces inherent in the design of the gauge. The same things can be said for other objects in the path of a shock wave. In order for the pressure measurements made with any gauge to be useful in relating pressure to response, it is first necessary that the gauge respond to the transient forces or pressures at least as fast as does the object. If the response of the gauge is slower, important pressure changes may go unmeasured. If the response is the same, all the pressure measured by the gauge, and no other pressures, will be important to the response of the object. If the response of the gauge is faster than the response of the object, something less than the pressure measured by the gauge will be significant for the response of the object under consideration. The gauge will have recorded more information than is necessary, and it will still be necessary to extract the information on pressure significant for the object from the measured pressures. This is possible only if one knows already the way the object responds to transient forces. This latter information is usually obtained by a combination of appropriate formulae and empirical measurements of responses of the object to controlled transient forces.

In practice it is usually considered best first to know the responses of the object under consideration and then to measure with a gauge which will more completely describe the actual pressure phenomena. In this way the meaningful pressure changes can be extracted from the physical data and at the same time the experimenter will be able to detect differences among physical stimuli before they become important to his experiments.

Only recently have serious studies been undertaken to determine the physical characteristics of human tissues that determine their response to vibratory energy.[5,6,7] These same characteristics largely control the response of tissues to transient energy. The response of the human body to transient forces has also been considered in Air Force studies related to the ejection seat and the rapid deceleration associated with aircraft crashes. Unfortunately, most of the important details have not been published. Perlman[8] has published some information about the response of the middle ear conduction apparatus to shock waves produced by a blank cartridge in a pistol. Otherwise, little is reliably known about the responses of the human body or its tissues to transient forces. The situation is further complicated by the fact that tissues, from what we now know, do not usually respond to large forces in a linear manner; that is, the response is not proportional to the forces applied. Much more information of this nature is necessary before reasonable correlations between blast phenomena and human responses can be made.

Because of all these difficulties, reliable correlations between the physical stimuli and response or injury have not been made even for experimental animals. (Only under the most fortuitous circumstances could one have expected measuring instruments to be operating at the right time and place either in battle or for an accidental explosion.) The collaboration of Miller,[1,9] and Hooker[10] during World War I yielded some information concerning pressures and injury. Miller used the baroscope and the phonodeik for his measurements. It was clear to these workers at the time, however, that the pressures as measured did not correlate with degree of injury when different sources of blast were compared.

Clemedson[11] more recently has experienced similar difficulty. Although he obtained, as a first approximation, a good correlation between lung injury in the rabbit and peak pressure of the explosion, he was not able to improve the correlation by including the duration of the pressure in

his calculations. He stated that it is practically easier to correlate injury with the physical stimulus by defining the stimulus in terms of the weight of the explosive charge and the distance from the explosion. In fact, much of the work reported by Zuckerman,[11] Benzinger,[18] and Desaga[14,15] is reported only in terms of weight of explosive charge and distance from the explosion. Desaga also reports one series in which, as the weight of the charge was increased from 25 kilograms to 2000 kilograms, the lethal limit for dogs increased from 4.25 meters to 25 meters, the peak pressure measured at the location of the dog decreased from 14.7 atmospheres to 5.2 atmospheres, and the duration of the positive pressure phase at the dog increased from 1.6 milliseconds to 11.8 milliseconds. In general, this is the kind of relation between pressure and duration of pressure one would expect to find for some injuries. The peak pressures required for serious or lethal injuries, given elsewhere in the literature, range from about 4 to 20 atmospheres. Thus there is general agreement as to order of magnitude, but there are disturbing discrepancies in detail. In order to resolve these differences, it will be necessary to know more accurately the transient response characteristics of body tissues and organs.

Little is said in the open literature about the pressures to which man may be exposed without immediate injury aside from temporary (and possibly permanent) hearing loss. Pressures, as measured by various instruments, to which men have been exposed without such injury range up to 1.6 atmospheres. In general it would appear that men prefer not to be exposed to peak pressures much above 3.5 to 7.0 pounds per square inch, or one-quarter to one-half an atmosphere.

It should be noted that the pressures cited above for man and animals do not include any estimates as to the proportions of blast pressure, shock wave pressure, and pressure doubling that are measured by the various gauges. In practice this is necessary because the gauges do not make such distinctions. It is not known whether this lumping of all pressures conceals any important physical variables. An analysis of the pressure field, such as the ingenious one employed by Miller[1] when he measured the propagation of the sound wave from the muzzle of a large gun, might well lead to useful approximations of the components of the pressure measured at any particular place in the pressure field.

V. Reported Effects of Blast Phenomena

Information on the effects on the body of blast phenomena can be classified according to:

1. Time injury appears
   - a. after one exposure
   - b. cumulative effects of many exposures
2. Causal relationship
   - a. direct result of physical event
   - b. secondary to other bodily changes
3. Portion or system of the body injured, e.g.
   - a. ear
   - b. lung
   - c. heart
   - d. abdominal viscera
   - e. skeleton
   - f. brain
4. The medium transmitting energy to the body
   - a. air
   - b. water
   - c. solid structures

Nearly all the literature dealing directly with blast is concerned with immediate or only slightly delayed injury incurred after a single exposure to

one or another of the forms of energy associated with blasts. Loss of hearing through repeated exposures to lesser quantities of peak energy is the exception. However, it appears useful to study this literature both for the limiting conditions for the present area of interest and for clues to profitable areas of study to determine any cumulative effects of blast phenomena of smaller magnitudes.

Immediate Injury

The Ear. Injury to the ear is the most commonly reported injury from blast energy transmitted to the body through air. Ear injuries are not mentioned in connection with solid-borne blast energy and those who have reported injuries from underwater blast note that the ear is rarely injured because the head is usually out of the water. Since the ear is the portion of the body most sensitive to vibratory energy in air, it is not surprising that it should be the part most vulnerable to blast and shock wave pressures in air. Two kinds of injury are noted: injury to the tympanic membrane and conduction apparatus, and injury to the sensitive cells of the inner ear. These injuries may occur singly or together. In many papers the statement is made that rupture of the tympanic membrane dissipates the energy and protects the inner ear. This statement has been questioned on the basis that the patients seeking medical attention sustained either rupture of the tympanic membrane or evident hearing loss. Clinical experience thus includes essentially all cases of rupture of the tympanic membrane, many of whom have no measurable residual hearing loss, and all cases without rupture in which large hearing losses occurred. There is no way of knowing how many ears escaped rupture and suffered either minor hearing loss or no measurable hearing loss after exposure to equivalent blast phenomena.

Satisfactory relationships between hearing loss and the physical dimensions of the blast phenomena have not been established. To a first approximation Murray and Reid[16,17] found that temporary hearing loss correlated best with peak pressures of the shock waves from artillery. Within the limits of the range of the pressure-time integrations of the shock waves from a variety of artillery weapons they found no significant dependence on duration of the shock pressures. They note that if such a correlation exists, it is masked by differences in susceptibility to temporary hearing loss among their subjects. There was a more consistent hearing loss pattern for a given ear with all weapons than for a given weapon with all ears.

Ruedi and Furrer[18,19,20,21] have reported a variety of animal experiments and observations on humans that are well worth reading. In general their experimental work has been of high quality but many of the theoretical conclusions they have drawn are open to question.

No protection against shock waves is provided by the intra-aural muscles since the duration of the shock wave is less than the delay from stimulus to contraction of the muscles. So far as is now known, little, if any, protection is afforded by ear plugs made of dry cotton wool. Nearly complete protection is provided by ear protectors that make an airtight seal at the entrance to the ear canal. A systematic long term study of the latter statement is warranted but should not delay the use of such protection.

The Lungs. Hemorrhage in the fine structure of the lungs is the next most frequent injury from blast phenomena in air. In experimental animals sacrificed soon after exposure, rib markings appear as alternate strips of hemorrhagic and normal lung surface. Clemedson[22] relates the hemorrhagic areas to the interspaces between the ribs.

In order to tear tissues and structures there must be either relative displacements among the tissues in excess of their elastic limit or the elastic

limits of the tissues must be altered in some way, such as by the heat produced in damping vibratory energy, to the point where usual stresses or strains will produce displacements that will tear. In the immediate injuries with which this section is concerned, displacements in excess of the normal elastic limit probably constitute the mechanism of injury. Such displacements may occur if adjacent tissues or structures respond to a common impulse with different amplitudes. They may also occur if adjacent tissues or structures respond with identical amplitudes but at different times with respect to the common impulse. Discontinuities in the medium in which a shock wave is traveling are encountered at the boundaries of the body, of tissues of various densities (muscle, fat, bone, etc.) and of air enclosed in body cavities. Energy is partially reflected and partially transmitted at such boundaries. The transient response characteristics of the structures or media at these boundaries determine the fate of the energy and whether there will be relative displacements among the structures for either of the reasons mentioned above.

In general, the more dissimilar the media at a boundary, the greater the relative displacements. In the fine structure of the lungs, many boundaries exist between air and the liquid-like tissues. It is thus not surprising that differential displacements sufficient to tear such relatively delicate tissues exist. This tearing is a direct result of the physical event.

Essentially the same changes in the lungs of men swimming are observed following underwater explosions. The mechanisms are the same. This observation indicates that the destructive energy enters the body directly through the chest wall rather than through the small orifices presented by the nose, mouth and trachea. Also, no lung injury was observed in dogs for explosions in air with the head exposed and the body protected or for explosions in water with only the head of the dog immersed. Desaga[18] reports survival without lung injury when only the opened trachea of the dog is exposed to an explosion in air that would have produced fatal lung injury in an unprotected dog.

The Heart. Lowering of the blood pressure, sometimes to the point of shock, slowing of the pulse and an increase in the respiratory rate have been frequently observed in experimental animals exposed to explosions.[10,11,18,23] The shock-like state occurs too rapidly to be associated with loss of blood in the lung tissue, so explanations have been sought through reflex mechanisms. Hooker believed that concussion of the brain* was responsible. Clemedson[24] has demonstrated that these immediate changes in circulation and respiration do not occur if the afferent vagus nerves from the lungs are cut or if only the head is exposed to the shock wave of the explosion. It would thus appear that the tissue injury in the lung induces reflexly through the vagus nerve the shock-like state with a slow heart-beat. The situation is later complicated by loss of blood into the lungs and reduced oxygen supply secondary to the reduced capacity of the lung for air.

Heart failure secondary to failure of the circulation of blood to the heart muscle has also been noted and sometimes appears to be related to sudden death in experimental animals. Prompt and careful post-mortem examination of such animals has shown obstruction to the circulation by small bubbles of air.[25] Entry of these air bubbles is presumed to be through the torn blood vessels in the lung tissue rather than through cavitation effects with release as bubbles of the gases dissolved in the blood and other tissues.

The nature of the injuries sustained from underwater blasts is the same as for air. Injury from shock waves transmitted through solid structures has not been reported.

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* Concussion of the brain is a condition characterised by some degree of unconsciousness and loss of certain reflex activities which is often observed following the application of a transient force (a blow) to the head. The term is usually reserved for those cases where the condition is not accompanied by tearing, bruising, or other readily visible injury to the brain. In experimental animals microscopic injury to nerve cells is often found. Since simple uncomplicated concussion of the brain is practically never fatal for man, it is not known whether such microscopic injuries also occur with concussion of the brain in man.

Abdominal Viscera. Hemorrhage into air-containing abdominal viscera, particularly the gastro-intestinal tract, has been reported following both air and water blast. As for the lungs, the basic mechanism for injury would appear to be relative displacements among tissues at boundaries where the medium changes abruptly from fluid to gaseous. In air, injury to the lungs occurs more easily than injury to the abdominal viscera. The energy transfer from air to the air-filled chest cavity may be expected to be much more efficient than it is to the abdominal viscera which more nearly resemble a fluid medium. There are also important differences in the body wall between the chest and the abdomen. The chest wall is more rigidly supported by the ribs with diaphragm-like spaces between the ribs, which may transmit rather than reflect energy from outside air to lung air. On the other hand, the abdominal wall, consisting of fat and muscle with little rigidity, will reflect energy brought to it through air.

Underwater explosions of mines near sailors swimming in water have been noted to produce more severe injuries to the air-filled abdominal viscera than to the lungs. In this case more energy is reflected from the air-like chest wall and less is reflected from the fluid-like abdominal wall. In some instances a second factor may be important in this regard. Shock waves in water tend to be reflected back away from the surface so that most of the energy is concentrated in the shape of a cone with its vertex at the surface of the water immediately above the point of explosion. A discrete shadow zone appears near the surface even relatively close to the explosion. Thus it is possible that quite different shock pressures reach the chest and abdomen of a man positioned vertically in the water. For the same reasons, a man lying horizontally at the surface of the water may escape injury.

The Skeleton. Injuries to the bony skeleton from shock waves reaching man through air or water have not been reported. On the other hand, shock waves reaching man through solid supporting structures have produced severe fractures and dislocations of the skeleton.[26,27] In practice the common situation for such injury consists of the shock wave energy from an exploding mine being conducted from the hull of a ship by a principal structural member to the platform on which a man is standing or sitting. For the standing man, the most common injuries are severe, often compound, fractures of the bones of the foot, ankle or lower leg. Dislocations of the knee joint occur with serious consequences. Usually such dislocations interfere with the major blood vessels to the lower leg. Gangrene results and amputation is required. Fractures above the knee are rare. Again the principle of injury by relative displacement among tissues is important. The response of the body for transient forces applied upward through the feet appears to be such that a relative displacement will either occur at or below the knee, or, if the transient jolt (rate of change of acceleration) is not too great, the body will be displaced as a whole without injury.

In a similar way shock transients applied to the base of the spine of a seated man can produce fractures and dislocations of the spine with paraplegia as a consequence. Although injuries to the lower extremities while standing and to the spine while seated are most common, other postures with varying degrees of contact with solid structures can produce other more bizarre injuries.

The Brain. The mechanism of injury to the brain from shock waves in air remains somewhat obscure. Both large and small hemorrhages in the substance of the brain and in the tissues surrounding the brain have been observed in both man and experimental animals.[28,29] Such injuries usually occur after exposure to extreme and nearly mutilating blast conditions. There is experimental evidence that under less severe conditions some of these hemorrhages are secondary to interference with the circulation to the brain by bubbles of air in much the same way as described above for the heart. In experimental animals,

brain injury is reduced, if not entirely eliminated, at pressure levels which are just lethal for all unprotected animals by protecting the rest of the body and leaving only the head exposed. In man, it is not known whether brain injury can appear independently of lung injury and air emboli. It appears that explosions in confined spaces or exposures near walls or embankments which produce pressure-doubling favor both kinds of injury. When brain injury is present, medical attention is often diverted from other injuries. Brain injury may manifest itself directly through signs in the peripheral nervous system or may be "silent." A diagnosis of concussion may be made only to have the patient die a short while later with a large fresh hemorrhage super-imposed on an old area of injury.[28,30] The possibility of cumulative direct concussive injury to the brain must certainly still be entertained even though on a one-shot basis the lungs appear to be more vulnerable than the brain. This is especially true because injured lung tissue cells are replaced in the healing process. Nerve cells are not replaced.

While brain injuries serious enough to lead to death rarely appear in the absence of other equally severe and mutilating injuries, lesser injuries are relatively common in battle. Exposure to blast phenomena often results in a syndrome (combination of symptoms and signs) characterized by anxiety, fear, strong startle reactions, bizarre tremors, automatic movements, headaches, amnesia, emotional instability, insomnia, restlessness, inability to concentrate, and generally reduced efficiency.[30-38] This syndrome may result from brain injury, hysteria, or both. Nearly all possible combinations have been seen and reported in the literature variously as "shell shock," "battle fatigue," cerebral blast concussion and hysteric-anxiety state. Similar, if not identical, syndromes appear in hyperthyroidism, mild hypoglycemia, some allergic conditions, after extended hypoxia, and in carbon monoxide, bromide, or lead poisoning.[39]

In clinical practice differential diagnosis between hysteric-anxiety state and organic changes associated with concussion is usually made on the basis of response to therapeutic trials and on the basis of the proportional severity of the several complaints comprising the syndrome.[40,41,42] These methods do better than chance but are far from infallible and they do not clearly include the possibility that a full-blown hysteric-anxiety state may well exist in a patient with considerable organic damage to the brain. Reliable objective tests to make this differential diagnosis do not exist but much effort is being expended to develop such tests.

Because of the ways in which various patients were routed for treatment during World War II, it is impossible to arrive at an estimate of the relative frequencies of the cases of psychological and physiological origin that existed. Some series of cases indicate that cerebral blast concussion syndrome was rarely caused by brain injury. On the other hand, authors who saw selected cases which had failed to respond to psychiatric treatment found evidence of brain damage in every patient.[43] About all one can infer is that sooner or later nearly all patients received appropriate treatment.

Other Injuries. Hemorrhages in other structures such as the nasal sinuses and large muscles have also been described. These injuries are usually minor compared to the simultaneously incurred injuries in other organs.

Cumulative Injury

Cumulative injury to hearing from blast, shock waves and high-intensity sound is well known.[44-51] Permanent hearing loss may be produced by all kinds of weapons, from small arms to heavy artillery. Clear cut quantitative relations between exposure conditions and hearing losses have not yet been established. However, the presence of the relationship is so clear that there is no excuse for failure to use presently available ear protectors.

Cumulative injury to other parts of the body has not been reported. In many ways the possibilities for such injury are similar to those encountered at close range to the high-intensity noise of jet engines as suggested in the BENOX Report.[55] In any event the problems involved in detecting and measuring such injury, if it exists, will be the same.

The effects of blast phenomena on performance and behavior will probably be similarly difficult to measure. Again the methods will be similar, if not identical, to those used to measure performance and behavior during or after exposure to high-intensity noise. Should functional deficiencies be detected, their causes, psychological or physiological, will be equally difficult to evaluate.

Much of the literature on blast injury deals with men on the receiving end of explosions and the danger to the individual is unambiguous. There has been little real or apparent danger in the past associated with blast from the soldier's own weapon. The soldier knew how to avoid such danger as did exist. It is quite conceivable that the blast, shock and noise associated with more powerful modern weapons could be associated with apparent danger to himself in the mind of the soldier. This could lead to psychologically-induced alterations in performance and behavior even though the real danger has not changed.

On the other hand, if the blasts associated with modern weapons significantly exceed those previously encountered, the possibility of physical or physiological influences on performance and behavior should be considered. As first steps, measurement of the blast and associated phenomena to which men are exposed and observation in the field for evidence of limitations on performance are certainly indicated.

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